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ORIGINAL ARTICLE

Three-dimensional unsteady natural convection and entropy generation in an inclined cubical trapezoidal cavity with an isothermal bottom wall

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Abstract Numerical computation of unsteady laminar three-dimensional natural convection and entropy generation in an inclined cubical trapezoidal air-filled cavity is performed for the first time in this work. The vertical right and left sidewalls of the cavity are maintained at constant cold temperatures. The lower wall is subjected to a constant hot temperature, while the upper one is considered insulated. Computations are performed for Rayleigh numbers varied as $10^3 \leqslant Ra \leqslant 10^5$, while the trapezoidal cavity inclination angle is varied as $0° \leqslant \Phi \leqslant 180°$. Prandtl number is considered constant at $Pr = 0.71$. Second law of thermodynamics is applied to obtain thermodynamic losses inside the cavity due to both heat transfer and fluid friction irreversibilities. The variation of local and average Nusselt numbers is presented and discussed, while, streamlines, isotherms and entropy contours are presented in both two and three-dimensional pattern. The results show that when the Rayleigh number increases, the flow patterns are changed especially in three-dimensional results and the flow circulation increases. Also, the inclination angle effect on the total entropy generation becomes insignificant when the Rayleigh number is low. Moreover, when the Rayleigh number increases the average Nusselt number increases.

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Nomenclature

Symbol	Description (unit)
g	gravitational acceleration (m/s^2)
H	height of the trapezoidal cubical cavity (m)
k	fluid thermal conductivity (W/m °C)
n	unit vector normal to the wall
L	length of the cubical trapezoidal cavity (m)
Nu	Nusselt number
N_s	dimensionless local generated entropy
Pr	Prandtl number
$\vec{q}$	heat flux (W/m^2)
Ra	Rayleigh number
S	dimensionless entropy generation
S'_{gen}	generated entropy (Kj/kg K)
T	dimensionless temperature $[(T' - T'_c)/(T'_h - T'_c)]$
T_o	bulk temperature $[T_o = (T'_c + T'_h)/2]$
t	dimensionless time $(t' \cdot \alpha/L^2)$
$\vec{V}$	dimensionless velocity vector $(\vec{V}' \cdot L/\alpha)$
x	dimensionless Cartesian coordinate in x-direction (x'/L)
y	dimensionless Cartesian coordinate in y-direction (y'/L)
z	dimensionless Cartesian coordinate in z-direction (z'/L)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
ΔT	dimensionless temperature difference
ϕ'	dissipation function
Φ	trapezoidal cavity inclination angle (degree)
υ	fluid kinematic viscosity (m^2/s)
$\vec{\psi}$	dimensionless vector potential $(\vec{\psi}'/\alpha)$
μ	dynamic viscosity (kg/m s)
$\vec{\omega}$	dimensionless vorticity $(\vec{\omega}' \cdot \alpha/L^2)$

Subscripts

av	average
c	cold
fr	friction
h	hot
Loc	local
th	thermal
tot	total
x, y, z	Cartesian coordinates

Superscripts

′	dimensional variable

1. Introduction

Natural convection in cavities of various geometries has taken considerable attention in the past few decades due to its many significant applications such as electronic components, cooling, heating and preservation of canned foods, solar collectors, nuclear reactors, double-panel windows and heat exchangers [1,2]. The study of natural convection in a trapezoidal cavity is very difficult compared with classical square or rectangular cavities due to the presence of inclined walls. This complex geometry needs an accurate and large effect in grid generation and code construction. However, many studies were available on natural convection concerned trapezoidal cavity. Lam et al. [3] performed experimental and numerical studies of natural convection in trapezoidal cavities composed of two vertical insulated sidewalls, an inclined cold top wall and a horizontal hot bottom wall. Kumar [4] studied experimentally the natural convective heat transfer in a trapezoidal enclosure of a box-type solar cooker by using the simple proposed correlations for a wide range of absorber-plate temperature. He concluded that the major advantage of this geometry was the absorption of a higher fraction of incident solar radiation falling on the aperture at larger incidence angles. Basak et al. [5] investigated numerically the natural convection in trapezoidal enclosures for uniformly heated bottom wall, linearly heated vertical wall(s) in presence of insulated top wall. The results were presented for wide range of Rayleigh numbers (Ra = 10^3–10^5), Prandtl numbers (Pr = 0.7–1000) and various tilt angles of side walls (φ). For linearly heated sidewalls, symmetry in flow pattern was observed. Average Nusselt number plots showed higher heat transfer rates for ($\varphi = 0°$) and the overall heat transfer rates at the bottom wall were larger for the linearly heated left wall and cooled right wall. A non-monotonic trend in average Nusselt number against Rayleigh number due to presence of multiple circulations was observed for ($\varphi = 0°$). Lasfer et al. [6] investigated numerically the steady natural convection of air flow in a two-dimensional side-heated trapezoidal room. The considered geometry had an inclined left heated sidewall, a vertical right cooled sidewall, and two insulated horizontal upper and lower walls. Computations were performed for seven values of the heated sloping wall angle, three different values of aspect ratio, and five Rayleigh number values. The results indicated a great dependence of the flow fields and the heat transfer on inclination angle, aspect ratio and Rayleigh number. A correlation between the average Nusselt number, Rayleigh number, heated sloping wall angle and aspect ratio was proposed. Basak et al. [7] studied numerically using penalty finite element method the natural convection flow in closed trapezoidal enclosures with linearly heated sidewalls and linearly heated left wall and cold right wall. In both cases the bottom wall was uniformly heated while top wall was insulated. Numerical results were obtained for various values of Rayleigh number ($10^3 \leqslant \text{Ra} \leqslant 10^5$), Prandtl number ($0.015 \leqslant \text{Pr} \leqslant 1000$) and inclination angles ($\varphi = 45°$, $60°$ and $90°$). It was found that, less intense circulations occurred in square cavity ($\varphi = 90°$) compared to other cavities ($\varphi = 45°$ and $60°$). They concluded that, overall heat transfer rates were larger for square cavity ($\varphi = 90°$) compared to other angles ($\varphi = 45°$ and $60°$) irrespective of heating patterns for side walls. Sahoo et al. [8] investigated numerically the heat loss due to radiation and steady laminar natural convection flow in a trapezoidal cavity having eight absorber tubes for a Linear Fresnel Reflector (LFR) solar thermal system with uniformly heated tubes and adiabatic top and sidewalls. Effect of emissiv-